4DVAR for Global Atmospheric Numerical Weather Prediction

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LONG-TERM GOALS

The long-term goal of this RTP project is to provide the warfighter with superior battlespace environmental awareness in terms of high fidelity four-dimensional (4D) depiction of the global atmospheric states. This situational awareness is a key aspect of information superiority in the DoD's strategic plan to ensure battlespace dominance in the 21st century. This goal is to be accomplished by providing NOGAPS[1] with best possible initial condition through the use of next generation global atmospheric 4D variational (4DVAR) data assimilation system, NAVDAS-AR[2].

OBJECTIVES

The objective of this project is to construct and transition a 4DVAR global atmospheric data assimilation system for NOGAPS to Fleet Numerical Meteorology and Oceanography Center (FNMOC). This system, NAVDAS-AR, represents the first operational, weak constraint, 4DVAR atmospheric data assimilation system in the world. In this context, "weak constraint" means that the atmospheric forecast model is not considered a "perfect" model, but rather is assumed to have errors. This enables the most optimal solution. NAVDAS-AR will provide high fidelity, dynamically consistent analyses for NWP model initialization and for warfighter support, and will be capable of efficiently handling large numbers of observations that may be irregularly distributed in space and time, and/or indirectly related to the model state variables (e.g., satellite radiances or wind vectors).

APPROACH

Our approach is to build on the prototype of NAVDAS-AR (Xu et al 2005, and Rosmond and Xu 2006) that has been developed and successfully applied to the global 4DVAR data assimilation application using the NOGAPS prediction model as a dynamic constraint. This project, which is a follow-up to a NRL ongoing in-house 6.2 data assimilation project, will expand this prototype to a next-generation operational global atmospheric data assimilation system. We will leverage the existing NAVDAS and NOGAPS infrastructures to provide the pre- and post- analysis processes. The system will be thoroughly tested using scientific studies, and comprehensive data assimilation and forecast experiments. Although the goals are ambitious, they are realistic because the theoretical basis for the project is already in place owing to great progress made in our 6.1 and 6.2 in-house data assimilation projects on variational data assimilation.

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[1] NOGAPS: Navy Operational Global Atmospheric Prediction System
[2] NAVDAS-AR: NRL Atmospheric Data Assimilation System – Accelerated Representer

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14. ABSTRACT
The long-term goal of this RTP project is to provide the warfighter with superior battlespace environmental awareness in terms of high fidelity four-dimensional (4D) depiction of the global atmospheric states. This situational awareness is a key aspect of information superiority in the DoD's strategic plan to ensure battlespace dominance in the 21st century. This goal is to be accomplished by providing NOGAPS1 with best possible initial condition through the use of next generation global atmospheric 4D variational (4DVAR) data assimilation system, NAVDAS-AR2.

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WORK COMPLETED

The following is a list of work completed related to this project during FY08.

1. Developed and tested new runscripts to run various NAVDAS-AR components under FNMOC's operational environment. This work is necessary to conduct OPS tests of NAVDAS-AR.

2. Implemented a revision control system, Subversion (SVN), to keep tracking various complex code changes in NAVDAS-AR.

3. Developed and tested a new multi-purpose preconditioner algorithm that significantly reduces the computational cost of many NAVDAS-AR applications, such as the second outerloop, the adjoint of NAVDAS-AR, the dynamical adjustment of observation error, and the estimation of analysis error.

4. Developed and tested new methods to treat time dependent observations during the pre-processing of observations to take the advantage of the four dimensional nature of NAVDAS-AR.

5. Developed and tested a software package that allows the inclusion of impact of model errors in NAVDAS-AR. This capability is critical for the ongoing effort to testing sophisticated model error covariance matrix into NAVDAS-AR.

6. Developed and tested a new procedure that allows a quick update of the adjoint of NAVDAS-AR whenever a new forward system is available.

7. Conducted many extensive data assimilation tests to test various components of NAVDAS-AR besides the parallel run with OPS.

8. Developed and tested a new semi-Lagrange and semi-implicit scheme used in the tangent linear and adjoint model of NAVDAS-AR to control the numerical noises in the moisture increment field.

9. Added six new observation types, SSMIS, METOP Infrared Atmospheric Sounding Interferometer (IASI) and ASCAT, AQUA Atmospheric Infrared Sounder (AIRS) and AMSU, and GOES rapid scan winds into NAVDAS-AR.

These FY08 accomplishments are critical for the AMOP transition of NAVDAS-AR to FNMOC.

RESULTS

The following results represent some highlights of the several significant accomplishments of this project during FY08.

An efficient and robust preconditioner for the second outerloop in NAVDAS-AR

NAVDAS-AR consists of 5 major components. There are: Quality Control (QC), Minimization (AR-4D), NOGAPS Forecast (FCST), Outputs (OUT), and Diagnostics (DIAG). The major computational cost of NAVDAS-AR is the minimization of a weighted least-squares cost function, made up of three computational components: an adjoint model integration, a background error covariance calculation,

and a tangent-linear model integration. The cost of these is primarily a function of the model resolution chosen, and surprisingly the cost is only weakly dependent on the number of observations. It is also a function of the number of outerloops to be used. To satisfy the operational time constraint, the minimization of the cost function has to be made extremely efficient without degrading the accuracy of the analysis. With the newly developed efficient and robust multipurpose preconditioner in NAVDAS-AR using the Lanczos connection, we require less than 50% of the computational cost in the second outerloop.

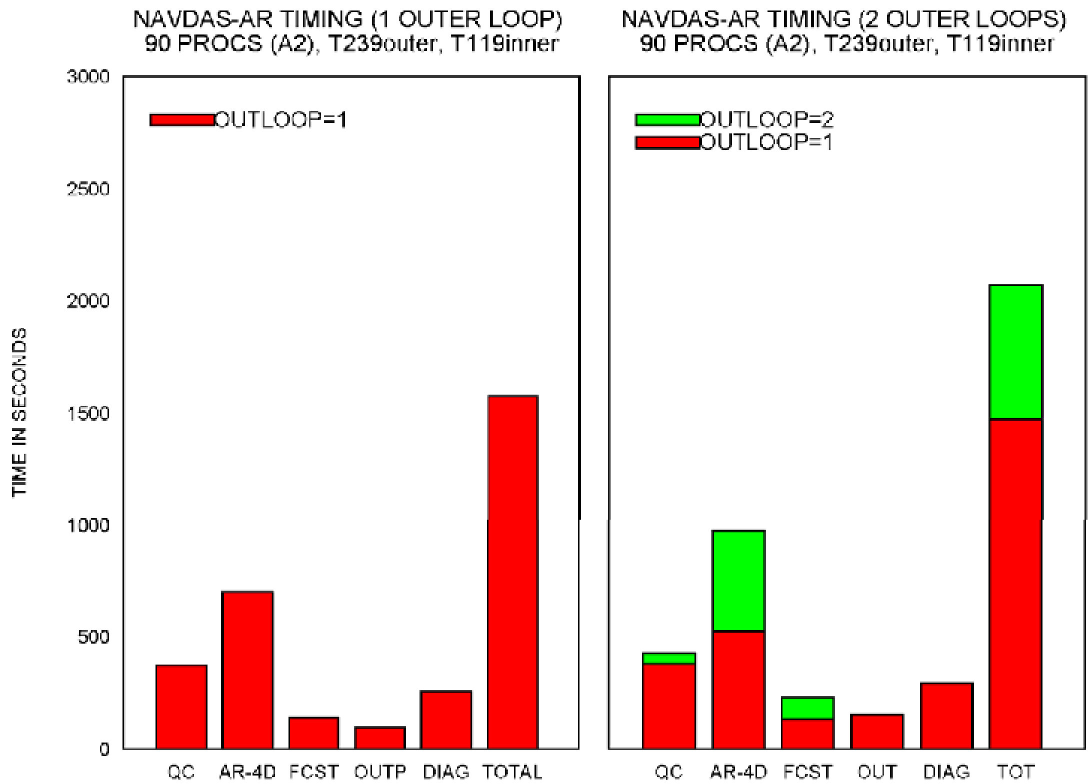

Figure 1: The typical computational costs to run various components of NAVDAS-AR with single (left panel) and double (right panel) outerloop are presented in the plots. The NAVDAS-AR timing was conducted on FNMOC's A2 with 90 processors. [The green bars represent the additional computational cost to run the second outerloop.]

NAVDAS-AR consists of 5 major components. There are: Quality Control (QC), Minimization (AR-4D), NOGAPS Forecast (FCST), Outputs (OUT), and Diagnostics (DIAG). Even with the 2nd outerloop, as indicated in Figure 2, we can still be within the operational time requirement (~ 2400 seconds) to run the standard NAVDAS-AR configuration using 90 processors on FNMOC's Linux cluster - A2.

The temporal aspects of the observation impact using the adjoint system of NAVDAS-AR

The most updated adjoint of NAVDAS-AR has recently been developed at NRL in Monterey. Instead of using the traditional line by line method to generate the adjoint of NAVDAS-AR, we take advantage of the self adjointness of the stabilized representer matrix and the existing routine to calculate the 4D matrix/vector in model space. Using these advantages, we construct the adjoint of NAVDAS-AR by

almost simply changing the order of subroutine calls used in NAVDAS-AR. Various validation tests suggest that the accuracy of the gradient test is mainly associated with the stopping criteria of the conjugate gradient solver and the use of double precision option in the compiler. It is important to note the fact that the observation sensitivity produced using the operational configurations is very similar to the ones produced using double precision and more stringent stop criteria in the solver routine. The computational cost of the adjoint without the preconditioner is comparable with the forward data assimilation problem. It is, however, much more efficient to calculate the adjoint sensitivity of observations with the use of the preconditioner obtained from the forward data assimilation problem. The successful development of the adjoint of NAVDAS-AR provides us a new powerful tool to monitor and diagnose problems in the data assimilation system. The results produced by the adjoint of NAVDAS-AR are similar in many ways to the results produced by the adjoint of NAVDAS as indicated in Figure 2. However, one big difference between the results produced by the two different adjoint systems is that the temporal dimension is presented in the adjoint of NAVDAS-AR. The results suggest that the late data has much more impact on the forecast. It is both important and interesting to find out why the late observations have bigger impact on the forecast.

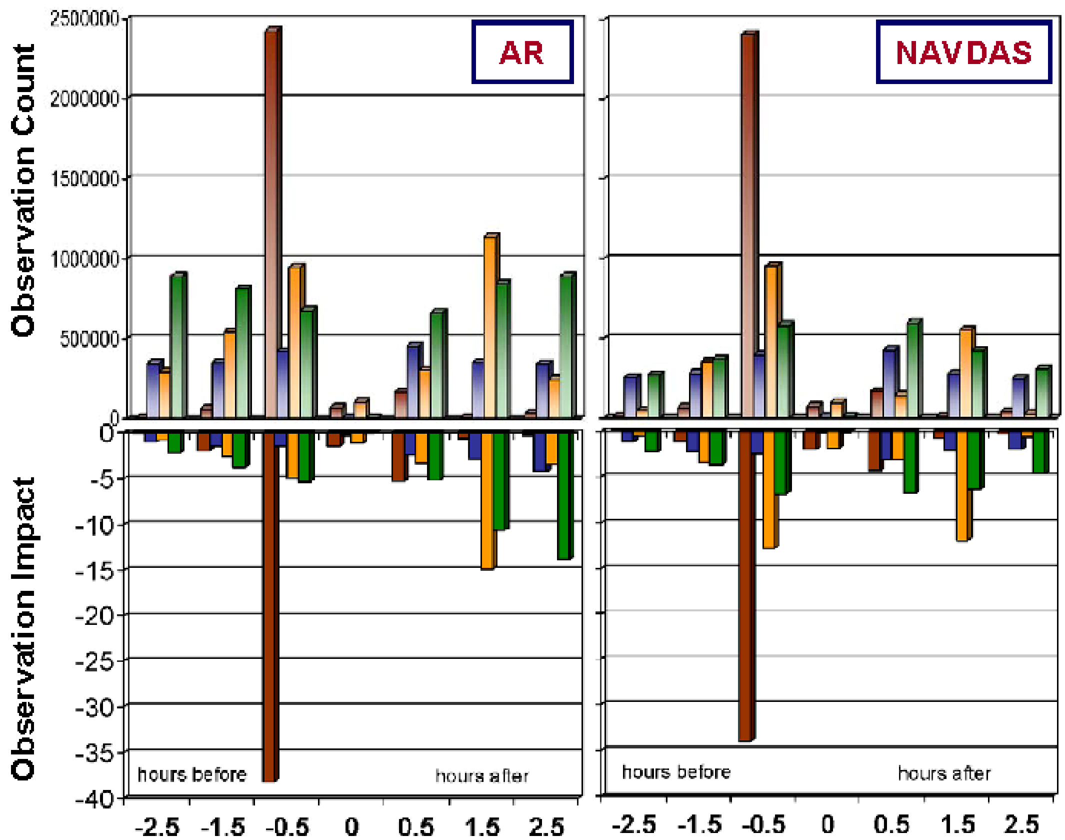

Figure 2: Left panel: NAVDAS-AR and right panel: NAVDAS. The 'Observation Counts' (plotted in the upper parts of the two panels) are for RAOB, AIRW, STAW, and AMSUA for each 30 min bin, respectively. The 'Observation Impact' are plotted in the lower parts of the two panels, where the negative values corresponding to positive impacts. In another word, the more negative the values the better impacts they provide.

Figure 2 represents a one-month average (8 April – 7 May, 2008) of the observation impact and the number of observations for 00Z. It is clear that AR is able to make use of many extra observations away from the analysis time (0.0) by comparing the upper parts of plots. Also, observations at end of the data assimilation window (i.e. +3.0) had more significant impact in reducing the forecasts error by comparing the lower parts of plots.

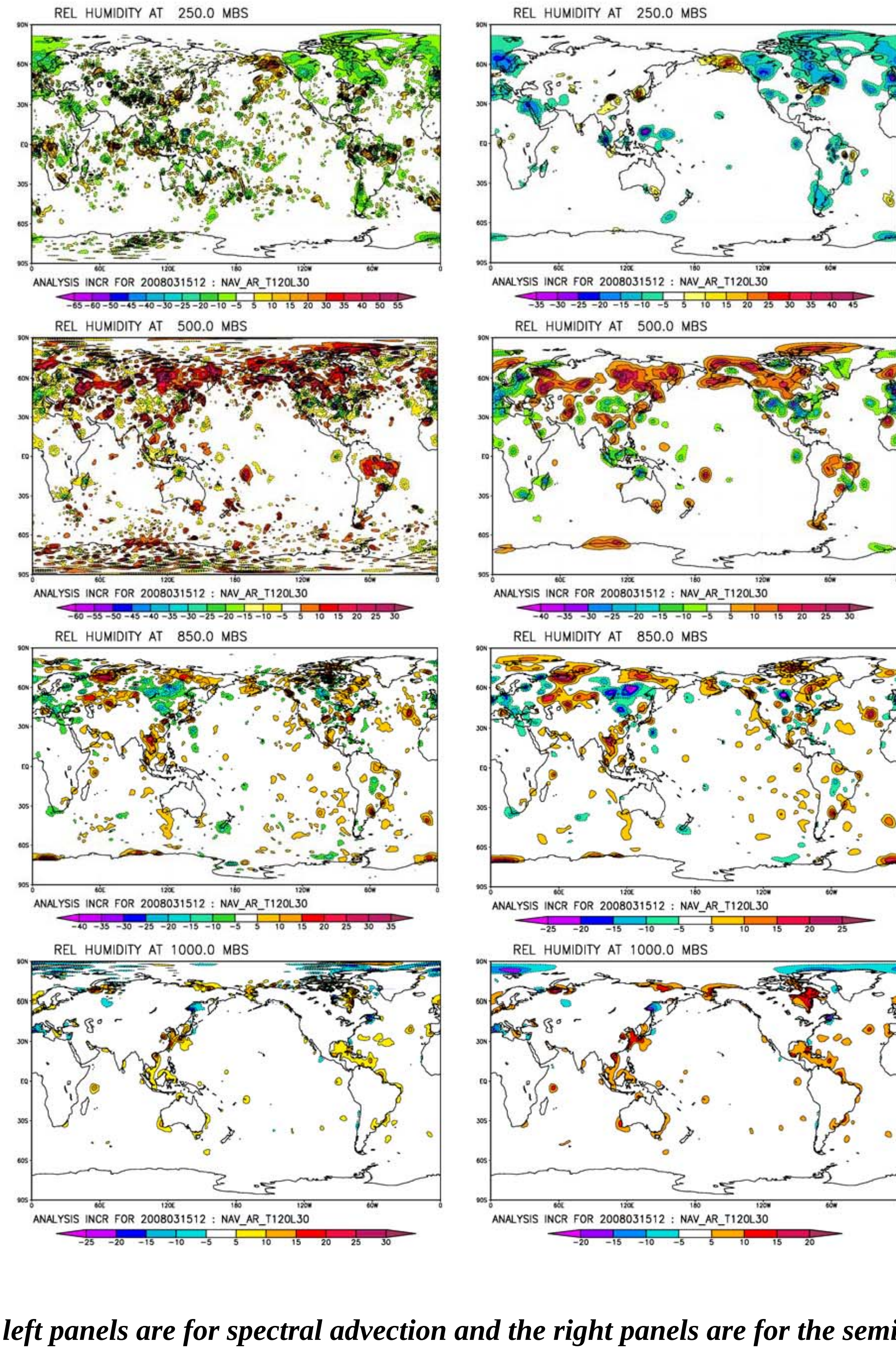

Figure 3: The left panels are for spectral advection and the right panels are for the semi_lagrangian and semi-implicit advection at 250 mb, 500 mb, 850 mb, and 1000 mb, respectively.

A semi-Lagrangian and semi-implicit scheme for the moisture in NAVDAS-AR

We have developed and tested a new advection scheme to effectively control the artificial noises, also know as the spectral 'ringing', in the moisture field. The spectral 'ringing' was caused by the use of coarse spectral resolution in the tangent linear and adjoint models of NOGAPS. With the new advection scheme, we were able to significantly remove the artificial numerical noises caused by the spectral algorithm that we used previously as indicated in Figure3.

Semi-operational tests of NAVDAS-AR

NAVDAS-AR is continuously running at real time on the FNMOC's IBM since middle of the September 2007 until the IBM was out of commission in July 2008. It is now running in real time on the FNMOC's latest A2-Linux cluster. Taking the advantage of the additional time dimension in the NAVDAS-AR, we have been able to continuously adding more observations during each data assimilation cycle.

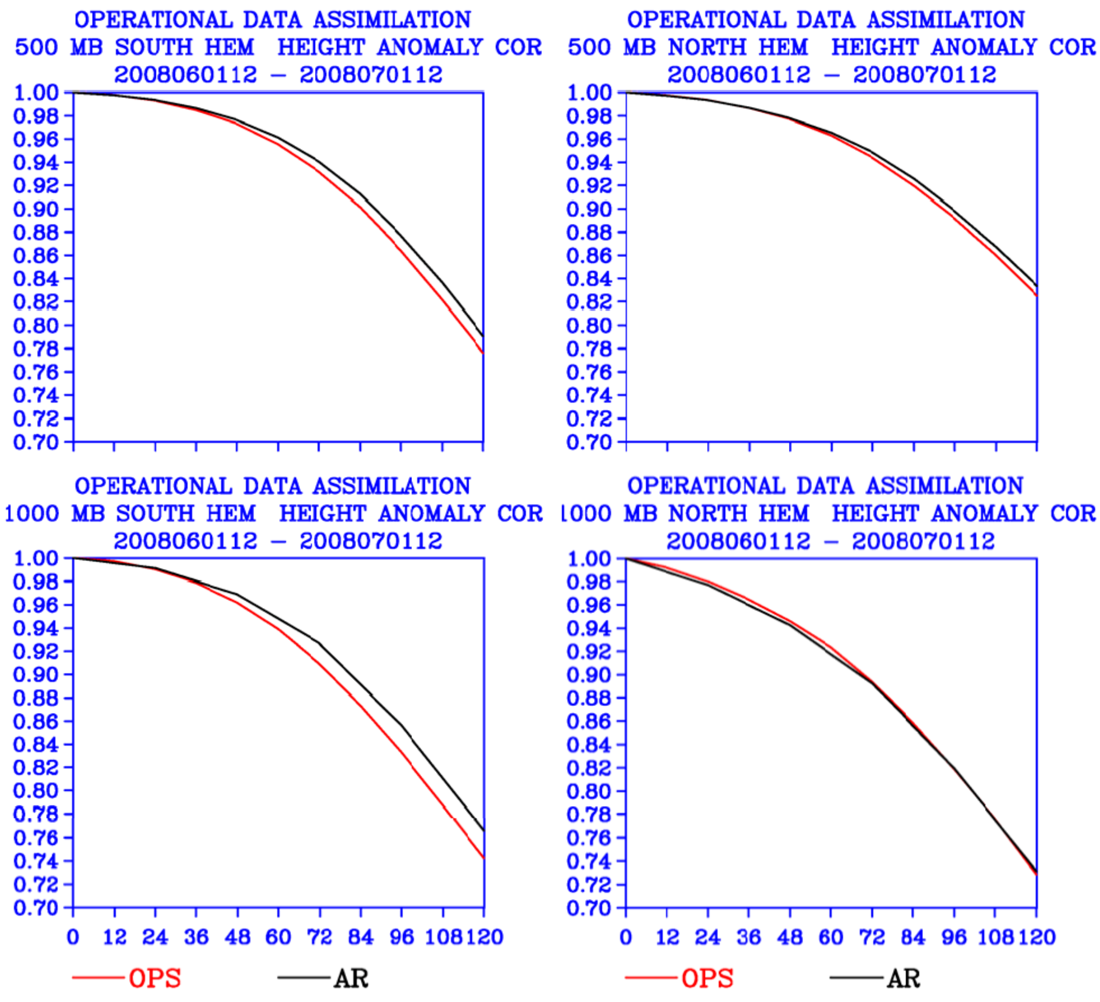

Figure 4: The plots represent anomaly correlations during 2008060112 – 2008070112 for both OPS and NAVDAS-AR. We only run single outer loop, i.e. some of the nonlinear effects are not reflected in the results. [OPS in red and NAVDAS-AR in black]

Various relevant statistics (e.g. Figure 4) have been collected and compared against the ones produced by other operational centers and our own OPS (NAVDAS) during each update cycle.

IMPACT/APPLICATIONS

The current operational data assimilation system at FNMOC, NAVDAS, is based on a three-dimensional variational (3DVAR) algorithm and is cast in observation space. The 3DVAR algorithm is widely used in intermittent cycling data assimilation for the analysis of global and synoptic scales around the world. It can handle relatively slowly evolving flows and observation platforms that sample heterogeneously in space, but assume that the observations are taken at the analysis time. However, highly intermittent flows that are not governed by simple balance relationships, and observation systems that sample irregularly in time, or with high temporal frequency, are not well accommodated within an intermittent 3DVAR framework but can be accommodated by a 4D data assimilation system. Furthermore, an intermittent 3DVAR algorithm produces a “snapshot” of the atmosphere at the center of the typical 6-hour observation time window, automatically making the resulting atmospheric analysis at least 3 hours old.

With NAVDAS-AR, a continuous picture of the atmosphere over the observation time window is produced, providing an atmospheric analysis at the end of the time window that is current rather than 3 hours old. Although NAVDAS has been quite successful, a 4D data assimilation system is a necessity to significantly improve not only the accuracy of the common operational picture required by the warfighter but also the timeliness of providing this more accurate picture to the warfighter. The advanced 4DVAR data assimilation algorithm, NAVDAS-AR, will provide the basis for this system. Only through 4DVAR algorithms can we truly exploit many of the observations from current and future observing systems. This is especially important for remotely sensed observations that are nonlinearly and indirectly related to the model state variables (e.g., satellite radiances and GPS radio occultation measurements). In addition, the computational efficiency of NAVDAS-AR with respect to the number of observations makes it more efficient than the NAVDAS 3DVAR system in handling the monumental increase in the volume of satellite data expected over the next decade.

TRANSITIONS

Improved algorithms and the new types of observations for NAVDAS-AR have been transitioned to the 6.4 component of this project, and will ultimately be transitioned to FNMOC by end of FY08 as the Navy’s next generation operational global atmospheric data assimilation system.

RELATED PROJECTS

Some of the technologies developed for this project will be used immediately to improve the current operational data assimilation system and the observational impact study in other NRL projects. The NAVDAS-AR has been recognized as a viable framework for various data assimilation applications, such as the ocean data assimilation system project (NRL base).

PUBLICATIONS

1. Chua, B., L. Xu, T. Rosmond, and E. Zaron, 2008: Preconditioning representer-based variational data assimilation systems: application to NAVDAS-AR. Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications (Eds by S. Park and L. Xu), Springer-Verlag, 305-318.
2. Xu, L., T. Rosmond, J. Goerss, and B. Chua, 2007: Toward an operational weak constraint 4D-Var system: application of the Burgers' equation. *Meteorologische Zeitschrift*, 16, 767-776.

PRESENTATIONS

1. Baker, N., B. Ruston, and T. Rosmond, 2008: Implementing Radiance Assimilation in NAVDAS-AR: Lessons Learned. International TOVS study conferences (ITSC), Angra dos Reis, Brazil, 7-13 May 2008.
2. Ruston, B., N. Baker, W. Campbell, T. Hogan, and X. Liu, 2008: Use of Hyperspectral IR Data in 4D Assimilation at NRL. International TOVS study conferences (ITSC), Angra dos Reis, Brazil, 7-13 May 2008.
3. Xu, L., B. Chua, and T. Rosmond, 2008: Toward a weak constraint operational 4D-Var system: application to the NAVDAS-AR. The 2nd Yoshi K. Sasaki Symposium on Data Assimilation for Atmospheric, Oceanic, and Hydrologic Applications. 16 – 20 June 2008, Bussan, Korea.
4. Xu, L., B. Chua, T. Rosmond, and N. Baker, 2008: Dual Formulations of Four-dimensional Variational Data Assimilation Applications. To be presented at the WWRP/THORPEX Workshop on 4D-VAR and Ensemble Kalman Filter Inter-comparisons, Buenos Aires, Argentina, 10-13 November 2008.

AWARD

N. Baker and L. Xu of NRL were the winners of the NRL 2008 Technology Transfer Award (also knows as the Loyalty Award) for their effort on the development and transition of NAVDAS-AR to operational customers.